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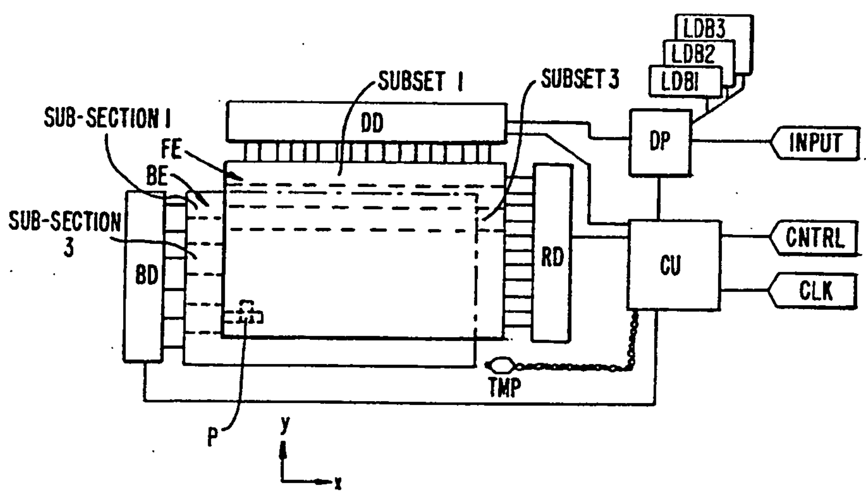

(57) Abstract

Compensation of the slow down of an LCD (FE) cell's response time when such devices are used in color sequential mode as an analog transmittance modulator to display colors of various shades is accomplished by a method, called deterministic-level-difference-boosting or DLDB for short. This method includes converting input data of ratios of color mixes into another set of pre-calculated or pre-measured signals before these signals are applied to the LCD (FE) to control its transmittance. By taking advantage of the periodical nature of transmittance change in color sequential operation, the compensated signal will minimize the error caused by slow-down of LCD response. Where the LCD response time is too slow to accomplish transition to a desired target transmittance level, the target level is scaled down for all colors to be displayed at the pixels to maintain correct color mixing ratio. Another aspect of this invention is a display device comprising a LCD front end (FE), a color light source (BE) and a unit (CU) that can perform the above described data conversion.

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DISPLAY DEVICE AND ITS DRIVE METHOD

CROSS REFERENCE TO RELATED APPLICATION

This application is a continuation-in-part application of patent application Serial No. 963,652 filed October 20, 1992, hereinafter referred to as the Parent Application, and is related to U.S. Patent Application Serial Number 07/812,730, filed December 23, 1991, herein referred to as the "Related Application," which is incorporated by reference in its entirety.

Background of the Invention

This invention relates in general to an efficient display device capable of displaying monochromatic, multi-color and full-color images of high brightness and resolution. Specifically, the invention relates to a front end unit with light shutters such as liquid crystal device (LCD) cells without color filters, where the LCD is illuminated by a back lighting source, which emits monochromatic light or light of multiple colors, such as the three primary colors of red, blue and green.

LCDs are one of the most widely used type of devices. However, most of the LCDs used today are monochromatic. While multi-color and full-color LCDs have been proposed, their development has been hindered by a number of technical difficulties. In most of the multi-color and full-color LCDs proposed, a back light source is employed. However, in most cases, the back light source employed is white light. Therefore, to produce composite images of different color, red, blue and green filter arrays have been used. For each pixel,

the white light directed towards a portion of the pixel is filtered to permit only red light to pass, and white light directed toward another portion of the same pixel is filtered to permit only blue light to pass and the white light directed towards the remaining portion is filtered to permit only green light to pass. Thus only a small part of the energy of the white light is transmitted through the LCD.

LCD cells respond slowly to voltages applied across them. Typically, when scanning voltages are first applied to a LCD cell, the cell has low transmission rate. The transmission rate rises slowly during the scanning cycle so that a low percentage of light is passed by the red, blue and green filters and transmitted through the LCD cells during the scanning cycle. This is a notable drawback of passive matrix type LCD color displays, where no drivers are used contiguous to the LCD cells for driving the cells.

To improve display quality, active matrix LCD cells are proposed by adding at least three thin film transistors for each LCD cell or pixel for accelerating the turning on and off of the three portions of the cell or pixel for light transmission of the three different colors. Such transistors and the data bus necessary to control them, however, are opaque and occupy a significant area of the LCD cell. In other words, the total transmission rate of the back light is lowered because of the reduction of the area of the cell that actually transmits light.

For the reasons above, it is difficult to use the above-described conventional designs to achieve efficient color LCD displays of high brightness, good color and high resolution. It is therefore desirable to provide an alternative design for color LCD displays which are inexpensive and where the above-described difficulties are avoided or alleviated.

In the Related Application, the above described difficulties are avoided by using an electronic fluorescent device as the back light source instead of a white light source with filters. This application proposes an extension of the invention in the Related Application.

Human eyes cannot see individual flashes when they are repeated faster than a frequency called *fusion frequency*. What is perceived by the viewer is the image integrated through time. Both motion pictures and cathode ray tube (CRT) picture tubes utilize this fact and present the picture in a frame-by-frame fashion. Input data is usually presented to the display device in a frame-by-frame manner. When the images are refreshed faster than this fusion frequency, most human observers will not detect image flickering. A color sequential scheme is a method where each frame of color image is further decomposed into three fields, one red, one green and one blue. These fields of color image are then cycled at a speed faster than the fusion frequency, and the image observed by the human viewer will be a color image. In other words, color mixing is performed in the time domain in color sequential displays. The fusion frequency depends on the brightness of display devices and their intended application. The current television standards are 50Hz for PAL and 60Hz for NTSC. Due to the close viewing distance, a computer monitor has a higher standard and a frame rate of around 70 Hz is considered to be desirable. For color sequential schemes, the field frequency will be three times higher than the frame frequency. For example, the field frequency for a 60Hz frame rate will be 180Hz.

A sequential display device known to those skilled in the art includes a light shutter front end and a color backlight source. Combining the effect of color changes of backlight pulses and the light trans-

mittance change of the individual light shutters, color images are displayed.

To perform the operation described above in a practical display, the light shutter needs to change the transmittance faster than 180 times per second to have a frame rate of 60Hz or higher. This corresponds to a shutter response time of about 5.5 milliseconds, close to the limit of response time of twisted nematic (TN) LCDs. In order to apply these LCDs in the color sequential scheme, response time management is of critical importance.

The response time of liquid crystal can be described by the following formula:

$$\tau_r = \frac{\eta d^2}{\Delta\epsilon V^2 - k\pi^2} \qquad (1)$$

$$\tau_d = \frac{\eta d^2}{k\pi^2} \qquad (2)$$

where τ_r, or the rise time, is the time it takes for a liquid crystal display (LCD) to change its transmittance in response to an applied signal from the time the signal is applied; τ_d, or the decay time, is the time it takes for the transmittance to change when the applied signal is removed; d is cell gap; ^{n} is liquid crystal twist viscosity; V is the applied signal voltage; and $\Delta\epsilon$ is dielectric anisotropy of liquid crystal. As can be observed from the above formula in equation (1), the response time depends on the signal level. As H. Okumura, *et al.*, reported in the *SID 92 Digest*, page 601, "A New Low-Image-Lag Drive Method for Large-Size LCTVs," due to dependency of response time on the applied signal, the response time for the transition from one intermediate gray scale to another intermediate

gray scale can be two to three times as long as a bi-level transition from fully ON to fully OFF. This slow-down of response time is most serious when each color needs to have many shades to display the large number of colors required in applications such as television, and it means that in color sequential operation the LCD needs to have a bi-level response time faster than about 5.5/3 = 1.8 milliseconds, assuming that response time for transitions between gray scales is three times that for bi-level transitions, to avoid color quality degradation caused by error in transmittance level of LCD pixels. However, this response time requirement is too fast for current TN LCD panels. A new driving method and system are therefore desirable in order for the TN LCDs to be used in color sequential display devices.

Summary of the Invention

One aspect of the invention is directed towards a display apparatus for displaying images in response to input signals. The apparatus comprises a front end unit and a front end control unit. The front end unit has an array of row electrodes and an array of column electrodes transverse to the array of row electrodes, said row electrodes overlapping column electrodes over a layer of light modulating material when viewed in a viewing direction to define consecutive rows of pixels at the layer, so that light transmittance through the pixels is controlled by electrical signals applied to the row and column electrodes, said light transmittance through the pixels defining a state of transmittance of such pixels. The front end control unit applies consecutively two or more sequences of transmittance control signals to the row and column electrodes to cause the light transmittance through the pixels to sequentially change one row at a time, defining a

scanning process sequentially scanning the rows of pixels during which one row of pixels is scanned at a time, each sequence corresponding to one of a plurality of colors, wherein each sequence of transmittance control signals controls the light transmittance of the rows of pixels for passage of light of the corresponding color.

The apparatus also include a back end unit and a back end control unit. The back end unit has two or more subsections generating light of said plurality of colors, each subsection overlapping at least one corresponding row of pixels in the front end unit when viewed in the viewing direction, so that light emitted by each subsection is directed substantially towards said at least one corresponding row of pixels. The back end control unit controls light emission of the subsections so that each subsection emits light of one of said plurality of colors at a predetermined time delay after the application of transmittance control signals in the sequence corresponding to such color to change the light transmittance of the at least one row of pixels corresponding to such subsection for passage of light of such color, and so that said predetermined time delays for light emission of all the subsections are substantially the same.

Another aspect is a method for displaying images in response to input signals employing said front and back end units described above. The method comprises applying two or more sequences of transmittance control signals to the row and column electrodes, each sequence causing the light transmittance through the pixels to sequentially change one row at a time, defining a scanning process sequentially scanning the rows of pixels during which one row of pixels is scanned at a time, each sequence corresponding to one of said plurality of colors, wherein each sequence of transmit-

tance control signals controls the light transmittance of the rows of pixels for passage of light of the corresponding color. The method also includes causing each subsection to emit light of one of said plurality of colors at a predetermined time delay after the application of transmittance control signals in the sequence corresponding to such color to change the light transmittance of the at least one row of pixels corresponding to such subsection for passage of light of such color, and so that said predetermined time delays for light emission of all the subsections are substantially the same.

In the preferred embodiment, by synchronizing the emission of color light signals by the subsections with the control of transmission of the light shutters, full color images having accurate intermediate gray tones are achieved with adequate refresh rate to avoid color quality degradation.

Display devices, such as the LCD, display images in response to input data signals. As discussed in the Related Application, the transmission rate of the LCD may be proportional to the magnitudes of the input data signals. However, as explained above, if the input data signals are applied directly without any compensation, the color images are degraded because the different gray tones cannot be achieved in time for a high refresh rate of about 180 Hz. Thus another aspect of the invention is directed towards a system for applying an adaptive boost (or cut) to the input data to compensate the signals before the compensated signals are applied to the electrodes controlling the transmittance of LCD to reduce error in gray tones.

Another aspect of the invention covers a display apparatus for displaying images in response to input signals. The apparatus comprises a front end unit, said unit defining therein a plurality of pixels,

each pixel including at least one light shutter, and a back end unit generating light toward the pixels in the front end unit. The apparatus further includes a device including a lookup table, said device generating transmittance control signals in response to the input signals according to the lookup table, said device providing said transmittance control signals to the front end unit to address each pixel in the front end unit and to control the light transmittance therethrough, said light transmittance defining a state of transmittance of such pixel; and means for causing the back end unit to produce light directed towards the front end unit to produce color images according to the input signals.

Yet another aspect covers a method for displaying images in response to input signals employing an apparatus comprising the front and back end units described in the paragraph immediately above. The method comprises generating transmittance control signals in response to the input signals and according to a lookup table; applying said transmittance control signals to the front end unit to address each pixel in the front end unit and to control the light transmittance therethrough, said light transmittance defining a state of transmittance of such pixel; and causing the back end unit to produce light directed towards the front end unit to produce images according to the input signals.

Brief Description of the Drawings

Referring to Figs. 1 through 6D, a preferred embodiment of the invention is illustrated. Like references will designate like or corresponding parts throughout the discussion of this embodiment.

Fig. 1 is a perspective view of the embodiment shown with the desired viewing position.

Fig. 2 is a functional block diagram of the embodiment.

Fig. 3 is a simplified time domain illustration of relationships between various waveforms and between different subsections of the embodiment.

Figs. 4A-4D illustrate in more detail the timing relationships in reference to one of the subsections of Fig. 3. In particular, Fig. 4A shows the back lighting pulses, Fig. 4B the activation signals for one of the rows of pixels generated by the row driver RD. Fig. 4C is a transmittance transition curve for one pixel where the activation signals of Fig. 4B are applied without compensation to the front end unit, and Fig. 4D is the transmittance curve for the same pixel after the activation signals have been compensated according to the invention.

Fig. 5 is a flow chart illustrating a method for compiling a lookup table for making the compensation illustrated in Fig. 4D.

Figs. 6A-6D are schematic circuit diagrams to illustrate different implementations for the lookup table to make the compensation illustrated in Fig. 4D.

Fig. 6E is a timing diagram to illustrate the boosting or cutting of input signals before they are applied to drive LCD cells, thereby reducing transient errors in gray tones.

Fig. 7A is a graphical illustration of the relation between light transmittance of a normally white LCD as a function of the voltage signal applied across it, where 1 represents the maximum light transmittance state and 0 the minimum light transmittance state.

Fig. 7B is a graphical illustration of the TFT gate pulses applied to a row of pixels during a number of scanning cycles, and of the light transmittance states during the cycles using only the DLDB scheme in Figs. 6C, 6D.

Fig. 7C is a graphical illustration of the TFT gate pulses applied to a row ofs pixel during a number of scanning cycles, and of the light transmittance states during the cycles using the DLDB scheme of Figs. 6A, 6B improved with color correction.

Description of the Preferred Embodiment

The preferred embodiment is a display apparatus including a front end unit FE and its associated drivers, a back end unit BE and its associated drivers, a device responsive to input data signals for generating transmittance control signals to address the pixels in the front end unit and to control the light transmittance therethrough, and means for causing the back end unit to produce light pulses. In the embodiment of Fig. 2, the device includes a data processing unit DP and interface port INPUT. An optional sensor TMP to sense the operating temperature of the front end unit may also be employed. The causing means includes control unit CU and interface ports CNTRL and CLK. The control unit CU responds to the control and timing information received from port CNTRL and CLK and produces control signals to various drivers and the data processing unit to operate the display device.

The front end unit FE is a matrix-addressable device such as an active-matrix liquid-crystal-display (AM-LCD). Each addressable unit is a light shutter whose transmittance can be controlled by signal fed from an input (not shown) through data driver DD. FE is controlled in a line scanning method where row driver RD will activate one line of pixels P (not drawn to scale in Fig. 2) at a time to receive data signals from DD. Each pixel occupies an area including one or more light shutters such as LCD cells. The pixels are arranged in an array of rows and columns along the X and Y directions respectively, each of the rows and columns being

a line of pixels. The scanning of FE is performed in a substantially sequential fashion. The back end unit BE is a light generating device such as a vacuum fluorescent display (VFD), a microtip fluorescent display (MFD) or a electron fluorescent display (EFD), whose light emitting area substantially covers and overlaps the light shuttering area of FE. The back end unit BE is further separated into about 20 or more subsections; a simplified version of only 4 subsections is illustrated by reference to Fig. 3. Each subsection corresponds to a number of rows or columns (i.e. lines) of pixels in the front end unit FE. Each pixel includes one or more light shutters such as LCD cells. To simplify the discussion, the scanning operation below will refer only to scanning of rows, it being understood that scanning column by column may be accomplished in essentially the same manner. Each subsection can be controlled by backlight driver BD to generate light pulses, of pulse widths shorter than about 1 millisecond, of three primary colors: red, green and blue. An optional diffuser layer DFU may be inserted between the FE and the BE to enhance the smoothness of the displayed image.

In operation, as illustrated in Fig. 3, the front end unit FE is scanned row by row sequentially. To scan a row, the row and data drivers RD, DD apply appropriate scanning and data signals to the row and column electrodes of FE unit row by row to change the levels or states of light transmittance of the rows of pixels. Where thin film transistors (TFT) are employed at the pixels, gate pulses are also applied to enable (activate) the scanning and data pulses to change the levels or states of light transmittance of the rows of pixels. When row N is scanned, data are loaded into pixels in row N, their TFTs are turned on by gate pulses, and these pixels will then start to change their

transmittance levels according to the newly updated data signal. For simplicity, only the activating LCD TFT gate pulses are shown in Fig. 3, to illustrate the invention. The same is true in Figs. 4A-4D, and 7B, 7C as well. Approximately at a delay Td after pixels of row N have been updated, the control unit CU controls the backlight driver BD to activate one or more BE subsections adjacent to row N to generate a light pulse of red, green or blue color. To produce one full color frame, the above process is repeated for all rows of pixels on the FE once for red subfield, and then once for green subfield and then once for blue subfield. When the frame rate is faster than about 60Hz, the synchronized change of pixel transmittance and the color of the backlight pulses produces color images when viewed from the viewing position indicated in Fig. 1.

As shown in Figs. 1 and 2, the front end unit FE includes an array of row electrodes RE, and an array of column electrodes CE that are transverse (preferably perpendicular) to the array of RE. To simplify the figure, only representative RE, CE are shown in dotted lines in Fig. 1. The two arrays of electrodes overlap over areas at a layer of light modulating material (not shown) in between RE and CE, such as liquid crystal material, at areas referred to herein as pixels, when viewed in a viewing direction V as shown in Fig. 1. By applying suitable scanning and data signals to the two arrays of electrodes, it is possible to alter light transmittance through each individual pixel. While the invention is illustrated herein by applying scanning signals to the row electrodes and data signals to the column electrodes, it will be understood that it is possible to apply scanning signals to the column electrodes and data signals to the row electrodes; all such variations are within the scope of the invention. Thus, where rows of pixels are indicated below, it will

be understood that the same may be true for columns of pixels as well.

In the embodiment of Figs. 1 and 2, the back end unit BE is divided into subsections, where each subsection overlap at least one row of pixels when viewed in the viewing direction V of Fig. 1, so that light emitted by such subsection will be directed to such corresponding at least one row of pixels. For simplicity in discussion, in Fig. 3, BE has only four subsections. As shown in Fig. 3, assuming that the front end unit has 480 rows of pixels evenly divided into four subsets with each subset having 120 rows, each subset corresponding to and overlap one of the four subsections. The pixel rows corresponding to subsection 1 of the back end unit illustrated in Fig. 2 are numbered from row 1 to row 120 of pixels. The LCD TFT gate will apply pulse 20 to row 1 and pulse 20' to row 120, where the time delay between pulses 20, 20' is about one quarter of the scanning cycle Tc for scanning all rows of pixels in the entire front end unit once. Other pulses (not shown) applied between the application of pulses 20, 20' are used to control light transmittance of pixel rows between rows 1 and 120. All of such pulses, together with pulses 20, 20', control the light transmittance of rows 1 through 120 for passage of a green light pulse to exhibit the green component of color image. The L.C. transmittance curve for row 120 is shown in dotted line 21', which is delayed relative to the transmittance curve 21 for row 1 (transmittance of row 1) by about 1/4(Tc). As shown in Fig. 3, the pulse 22 is applied by the LCD TFT gate to row 121 in subset 2 (corresponding to subsection 2 of the back end unit) after pulse 20', and pulse 22' is applied to row 240 at about 1/2(Tc) after pulse 20, and the transmittance curve of row 240 is delayed relative to transmittance curve of row 121 by about 1/4(Tc). Therefore,

when the back light pulses 32 are emitted by the corresponding subsection of the back end unit, the transmittances of the rows 1 through 120 (i.e. those in the subset 1) are substantially at their stable transmittance level whereas the rows 121 through 480 are not at their stable transmittance level. If the front and back end units are each divided into many more subsets and subsections than four, such as 20 or more, then the delay between the transmittance curves is reduced to 5% or less, rather than 25% or 1/4 of Tc as illustrated in Fig. 3, and then the transmittance curves such as 21. 21' of rows of pixels may all be made to substantially converge. In such event, the time shift between the transmittance curves may be ignored, so that the back light pulses 32 may be considered as generated at a fixed time interval Td after the application of the LCD TFT gate pulses.

The above described scheme is advantageous in that the generation of the back light pulses 32 is greatly simplified since their timing may be fixed at a particular delay in reference to a particular scanning pulse applied to the corresponding subset of rows of pixels. In the preferred embodiment, all of the subsections are caused to generate back light pulses at substantially the same delay after the application of the scanning and data signals to the pixel rows overlapping and corresponding to such subsection, where such delay may be Tc or a time interval slightly less or more than Tc. In other words, Td may be substantially equal to or slightly less or more than Tc.

A color sequential display device is illustrated in Fig. 1. The device includes a light shutter front end FE, such as an LCD, and a color backlight source or back end unit BE. As discussed above, the back end unit is separated into multiple subsections. Each of these subsections can independently generate light pulses of

red, green and blue color. The LCD front end functions as a matrix of light shutters controlling the transmittance of backlight pulses at each pixel. The shades of various colors are achieved by controlling the mix of red, green and blue lights. According to the required color mix, the transmittance of each LCD pixel is modulated in a periodical fashion, in synchronization with the backlight color pulses (Figs. 3 and 4). Combining the effect of the color change of backlight pulses and the transmittance change of each individual pixel, color images are displayed when the device is viewed in the viewing direction V, as indicated in Fig. 1.

In the display device shown in Fig. 1, the sequence and amount of transmittance level changes depends on the required R/G/B mix and is deterministic for any given color/brightness. This fixed sequence will be repeated until the information displayed by the pixel is changed. As long as the field cycle time is longer than the bi-level response time of the LCD front end, it is always possible to change the LCD input data signal or, more specifically, to boost or reduce (cut) the difference between two successive data signals, such that toward the end of each scanning cycle the transmittance of the pixel reaches the desired level. Due to the deterministic nature (explained below) of the time sequence between the transmittance level transitions, the amount of boost or compensation to the data signal can be predetermined by calculations and measurements. If the backlight or back end unit is partitioned into many subsections, each corresponds to a roughly equal number of scan lines in the LCD light shutter front end, and each subsection is to be pulsed at a fixed delay after the corresponding LCD lines of pixels are scanned by the signal of the corresponding color field of the

subsection, then the frame refresh rate of the device can be up to

$$\frac{N}{3(N+L)\tau} \qquad (3)$$

where N is the number of subsections in the backlight unit; L is a number larger than or equal to 1 and is related to the time between backlight pulses and the time pixels are addressed by data of the next field; τ is the bi-level response time of the LCD light shutter front end; and the factor 3 is for the red, green, blue three-color subfields. Based on this formula, assuming N=20, L=2, then the bi-level response time required for the LCD front end of a 60Hz frame rate color sequential display will be faster than about 5 mS for both the rise time and the fall time.

Based on the above observations, a new driving method called deterministic-level-difference-boosting (DLDB) and its associated structure are proposed in the current invention. The scheme of the current invention will relax the response time requirements of the light shutter front end in color sequential devices such as the one shown in Fig. 1. With the scheme of the current invention, a data processing unit DP will boost or reduce the difference between various gray scale signal levels by amounts predetermined through experiments and calculations such that the light shutter transmittance will change from any given starting level to any given target levels at a fixed time delay Td after the application or activation of the signals to the row and column electrodes RE, CE in FE, where Td is substantially equal to or slightly shorter than the field cycle time Tc (Fig. 4D). Source input signals representing ratios of red, green and blue color mixes will be converted to level-difference-boosted data through

parameter set calculations, table lookup or other data processing techniques. These boosted (reduced) signals are then applied to the front end light shutter to control the transmittance of each individual pixel. The corresponding subsections of the back end lighting unit will then be controlled to produce light pulses of appropriate color delayed approximately by Td after the application of a signal to a corresponding portion of the front end light shutters. Under the DLDB scheme, the frame rate will be determined mainly by the bi-level response time of the LCD, not the number of desired gray levels. For simplicity, as in Fig. 3, only the back light pulses R_1, G_1, ... etc, and TFT enabling gate pulses G_{R1}, G_{G1}, ... etc are shown in Figs. 4A, 4B, to illustrate the timing relationship between the addressing of the front end unit FE (to change light transmittance level or state) and the light emission of the back light unit BL.

From the above, if the number of subsections is sufficiently large, for example 20, then the elapse time Td between the signal application to the LCD pixels and the backlight pulses can be considered as fixed throughout the screen. As discussed below, taking advantage of this fixed elapse time, and in reference to Figs. 4A-4D, the drive signals (such as the input data signals from another source, not shown) of LCD pixels can be boosted or reduced (cut) by a predetermined amount to new signals that correspond to levels B1, B2, B3 that would be reached upon settlement without transition time restriction such that, at a delay Td after the signals are applied, the transmittance of the pixel will reach the desired gray transmittance levels L1, L2, L3 from the given starting level. L1, L2, L3 are three of the many gray levels that are possible. In other words, the original signal which corresponds to the value required for the pixel to settle to the desired transmittance

level after a prolonged delay, regardless of the starting transmittance level before the signal application, will be changed to a value that will allow the pixel transmittance to reach the desired level from the particular starting level, at an elapsed time of exactly Td after the signal has been applied.

The other factor affecting the response time of an LCD is its working temperature. To minimize the error caused by such environmental factors, another aspect of this invention is about a method and structure of combining sensors, such as thermocouple, placed near the front end unit, and a controller such that the controller will use the sensor's output to control the amount of level-difference-boosting by selecting appropriate lookup tables, changing coefficients used by the data processing unit, and so on.

To eliminate flickering of the displayed images, the device needs to repeat the r/g/b subfields at a rate of over 180 field per second or less than about 5.5 milliseconds per field. As illustrated in Fig. 4C, due to the dependence of LCD response on the differential data signal level between subsequent fields, if a TN LCD with a bi-level response time of about 5 mS is used in the above-described scheme, errors (E2, E3) in transmittance level will happen for intermediate gray level transitions between subfields. This differential signal level dependence of TN LCD will either cause the color quality to degrade or will limit the number of colors that can be displayed faithfully.

As indicated by the above formulas, the amount of boost (reduction) will be higher for smaller gray scale transitions, *i.e.*, the amount of boost depends not only on the target gray scale level but also on the initial start gray scale level. In other words, both the starting transmittance level or state before scanning and data signals are applied to the row and

column electrodes and the target transmittance level or state reached after the application will affect the amount of boost or cut needed. The exact level-difference-boosting function can be calculated in the design phase through detail modeling of liquid crystal behaviors, or it can be actually measured through different procedures. One possible procedure is shown in the flow chart of Fig. 5. The determined function can then be captured in lookup tables or in sets of parameters that can be built into the signal processing unit of the display device.

Due to the temperature dependence of the LCD response time, there can be multiple versions of level-difference-boosting functions or lookup tables, each optimized for a specific range of operating temperatures, as is indicated by LDB1, LDB2 and LDB3. During the normal operation of the display device, the control unit will select a particular level-difference-boosting function LDBx based on the output of temperature sensor TMP placed near the front end unit, the data processing unit DP will then convert the data received from the INPUT port into level-difference-boosted signals through function LDBx. These level-difference-boosted data signals will then be sent to the data bus driver DD to control the transmittance of the pixels in the front end unit FE.

Figs. 6A, 6B show two types of DP implementation of table lookup method applicable to adjust the input data signals applicable to each pixel. Fig 6A is a direct lookup where IN is the connection to the INPUT data port. Generally, the data for controlling the transmittance of a pixel can be further separated into R/G/B portion. The control unit CU presents the control signal FIELD to select the signal for red, green or blue color field. If DLDB is implemented as a memory device then IN and FIELD will serve as the address and the data

read out of the memory device will be the OUT which will then sent to the LCD data bus driver DD for controlling the transmittance of the pixel concerned.

Several DLDB lookup table can be integrated into one memory device as shown in Fig. 6B where the extra 2 bits address input T, generated by the control unit CU, further partition the memory device into four different tables each optimized for a specific temperature ranges.

A different implementation of DP utilizing finite state machine theory is shown in Fig. 6C. This implementation is based on the observation that the amount of signal boost or cut can be determined from knowledge of previous states of a LCD light shutter pixel and the current input. In Fig. 6C, two state memory buffers STB1 and STB2 are used to store the state of previous LCD pixel transmittance states, where STB1 stores the state of the last state (ST1) and STB2 stores the state before the last state (ST2). The level of state memory can be 1 and does not have to be 2. Although the light transmittance levels or states resulting from the signal conversion will be more accurate with more levels of state memory, the improvement of accuracy will diminish very quickly. In practice the two state memory can be implemented in one memory device STB where ST1 occupies one part of each word, for example the least significant J bits, while ST2 occupies other part of the word, for example, the most significant K bits. The width J is generally larger than or equal to width K and shorter than or equal to the width I of signal IN. For example, I=6, J=4 and K=2 may be a practical choice. In operation, the input data IN together with ROW and COL, representing the row and column position of the current data IN, are presented to the data processing unit DP. ROW and COL are used to address the state memory buffer STB.

The previous states ST1, ST2 of the pixel data currently being processed will show up in the output port of state memory. Combined with input data IN, states ST2 and ST1 will address the proper entry in state transition table STBL to produce the output OUT, ignoring the block NSG for the moment. The entry in STB corresponding to the ROW, COL entry will also be updated by the new input data IN such that the most significant K bits of ST1 become the new ST2 (ST2') and the most significant J bits of IN become the new ST1 (ST1'). ST1', ST2' are written back to the state memory buffer STB for later use. Alternatively, a next state generation circuit NSG may be used to derive the next states ST1', ST2' from the input IN and supply such states to state buffer memory STB, which later supplies stored states ST1, ST2 to STBL.

An alternative to Fig. 6C is shown in fig. 6D. Here the state memory includes ST as opposed to ST1 and ST2. The generation of next state ST' is from state transition table STBL as opposed to from bit shifting of IN and ST1. A feedback path applies the next state ST' to the buffer STB. Many other variation of Fig. 6C and 6D are possible.

When the LCD response time is shorter than the scanning cycle Tc, implementations shown in Fig. 6C and 6D are more general than the ones shown in Fig. 6A and 6B in that they do not require knowledge of the color of current field and therefore are not confined to a fixed sequence of transmittance change. In the situation where the information to be displayed by a pixel changes, the schemes shown in Fig. 6A and 6B will produce extra transient errors after each change while the schemes of Fig. 6C and 6D will not. Actually, the scheme shown in Fig. 6C or 6D can be applied to conventional LCD displays with a monolithic back end light source to improve their gray scale response time and is

not restricted to the color sequential operation as discussed in this invention. As shown in Fig. 6E, after the input signal (solid line signal) in the input signal sequence is boosted or cut using the circuits of one of Figs. 6A-6D, the level-difference-boosted signals (dotted line signals) in the sequence of transmittance control signals are applied to the data driver block DD for application to the front end unit.

When the LCD response time is slightly slower than Tc, the implementation shown in Figs. 6C and 6D can no longer produce correct color mixing ratio, since Tc is shorter than the LCD response time, it may not be possible to complete the transition between two arbitrary subsequent transmittance levels. However, the implementation shown in Figs. 6A and 6B can still produce correct color if a color correction scheme is employed. The color correction scheme is based on the fact that the rise time τ_r (formula shown above) can be accelerated by the applied signal beyond the bi-level response time. Therefore, in a normally white mode LCD (transmittance to signal voltage curve shown in Fig. 7A) where the OFF state of the LCD represents the state of highest transmittance while the ON state of the LCD represents the lowest transmittance, the lowering of the LCD transmittance can be accelerated by raising the applied signal voltage. This attribute allows one to control the color mixing ratio, or the accuracy of the color, by suppressing turning on (or lowering transmittance) transitions. An example is shown in Figs. 7B and 7C. Fig. 7B is a graphical illustration of the TFT gate pulses applied to a row of pixels during a number of scanning cycles, and of the light transmittance states during the cycles using only the DLDB scheme described above in reference to Figs. 6C, 6D. As shown in Figs. 7B, 7C, the target transmittance levels or states are labeled L_R, L_G, L_B. Fig. 7C is a graphical illustration

of the TFT gate pulses applied to a row of pixels during a number of scanning cycles, and of the light transmittance states during the cycles using the DLDB scheme of Figs. 6A, 6B improved with color correction. Fig. 7B illustrates a case where LCD response speed is slower than Tc and a DLDB scheme such as shown in Fig. 6C is used. As illustrated in Fig. 7B, the error in color mixing ratio is created since in every transition the DLDB scheme shown in Fig. 6C will try to minimize the error but fail to do so in certain transitions since the LCD response speed is really slower than the time Tc allocated for it to do the transition. Thus, the color green turns out to be brighter than the color red by the ratio 8/7, even though according to the specified ratio (R,G,B= 10,8,0), the red color should be 10/8 times brighter than green color in the image. As illustrated in Fig. 7C, a table lookup scheme such as those schemes shown in Figs. 6A and 6B can make sure the three color transition is such that, while the brightness may be sacrificed somewhat, the color mixing ratio is not changed. This can be achieved by incorporating correct judgment criteria in an algorithm such as the one shown in Fig. 5 which can be used to create the lookup table.

For example, the loop can consist of first determining the transmittance for one of the OFF transition (or raising transmittance) as compared to the desired level of transmittance. The ratio between this actual transmittance level and the desirable transmittance level will be used to modify the target transmittance level of the other two colors. For example, if the desired level of transmittance is 10-8-0 for red-green-blue and the actual achievable OFF transition can only raise the transmittance from 0 to 7, then the new transmittance mix becomes 7-5.6-0. These two sets of transmittance states 10-8-0 and 7-5.6-0 will produce the same color mixing ratio but with different brightness.

Using the new target transmittance data (7-5.6-0), the loop is continued to calculate the signals to be applied to the front end unit pixel for accomplishing the transition from 7 to 5.6 and from 5.6 to 0. In this case, since both of these are ON transitions (lower transmittance) they can be accelerated by raising the applied signal levels. In situations where one of these two transitions cannot be accomplished through boosting the signal differences, a new set of transmittance level mix is determined by scaling down all three transmittance with a common multiplying factor such as the case where the transmittance is scaled down from 10-8-0 to 7-5.6-0. Theoretically, the color correction loop should complete in two cycles, since within three transmittance levels there can only be two transitions raising transmittance. In reference to Fig. 5, during the step in determining whether the color red is correct, part of the decision is whether there is adequate time for the LCD to complete the transition. If there is insufficient time, then a scale factor is applied to scale up or down the target level to be achieved after the transition. For example, if a transition from 0 to 10 is not possible, while from 0 to 7 is possible, the target level is scaled down to 7 from 10 in order to determine whether the red color is correct. Then this scale factor is applied as well to the other two colors, unless the transition for any one of green and blue colors calls for a larger scale factor. If it is desired for the same scale factor to be applied to all pixels, then one would simply scan through all of the color data to be displayed to determine the value of the largest scale factor necessary for the transition with the largest dynamic range in the data, and then scale down the target transmittance levels or states for all incoming data with such scale factor. Then the signals for controlling the LCD transmittance levels are

obtained from the DLDB lookup table using such scaled down target levels. All such and other variations are within the scope of the invention.

While the invention has been described by reference to various embodiments, it will be understood that various modifications may be made without departing from the scope of the invention which is to be limited only by the appended claims.

WHAT IS CLAIMED IS:

1. A display apparatus comprising:

a front end unit having an array of row electrodes and an array of column electrodes transverse to the array of row electrodes, said row electrodes overlapping column electrodes over a layer of light modulating material when viewed in a viewing direction to define consecutive rows of pixels at the layer, so that light transmittance through the pixels is controlled by electrical signals applied to the row and column electrodes, said light transmittance through a pixel defining a state of transmittance of such pixel;

a front end control unit applying consecutively two or more sequences of transmittance control signals to the row and column electrodes to cause the light transmittance through the pixels to sequentially change one row at a time, defining a scanning process sequentially scanning the rows of pixels during which one row of pixels is scanned at a time, each sequence corresponding to one of a plurality of colors, wherein each sequence of transmittance control signals controls the light transmittance of the rows of pixels for passage of light of the corresponding color;

a back end unit having two or more subsections generating light of said plurality of colors, each subsection overlapping at least one corresponding row of pixels in the front end unit when viewed in the viewing direction, so that light emitted by each subsection is directed substantially towards said at least one corresponding row of pixels; and

a back end control unit controlling light emission of the subsections so that each subsection emits light of one of said plurality of colors at a predetermined time delay after the application of transmittance control signals in the sequence corre-

sponding to such color to change the light transmittance of the at least one row of pixels corresponding to such subsection for passage of light of such color, and so that said predetermined time delays for light emission of all the subsections are substantially the same.

2. The apparatus of claim 1, said apparatus displaying color images in response to a time sequence of input data signals each containing information relating to the desired state of transmittance of pixels at a particular time, said front end control unit further comprising a compensation circuit that modulates said input data signals to generate transmittance control signals for controlling transmittance states of pixels at at least one particular time as a function of at least two input data signals in the time sequence, said at least two input data signals containing information relating to the desired states of transmittance of pixels at at least two different times.

3. The apparatus of claim 2, wherein said front end control unit generates a transmittance control signal in response to a corresponding input signal in said time sequence of input signals for controlling the state of transmittance at said at least one pixel, so that said at least one pixel exhibits a time sequence of corresponding states of transmittance in response to said time sequence of input signals, said circuit including a storage unit for storing information related to at least one state of said time sequence of transmittance states for said at least one pixel, so that when an input signal subsequent to the one corresponding to the stored state is applied to the circuit, said circuit provides a transmittance control signal that is a function of the stored transmittance state and of such input

signal, thereby reducing transient errors in the gray tones of images displayed.

4. The apparatus of claim 3, wherein said circuit is a state machine.

5. The apparatus of claim 2, said circuit including a lookup table.

6. The apparatus of claim 1, wherein said front end control unit applies said transmittance control signals to at least one pixel periodically at a period Tc, and wherein said predetermined delay is substantially equal to or slightly less than Tc.

7. The apparatus of claim 1, further comprising at least one temperature sensor adjacent to the front end unit to sense the temperatures of the front end unit, wherein said front end control unit generates the transmittance control signals as a function of the temperature sensed by the sensor.

8. The apparatus of claim 1, said front end control unit includes a circuit for generating, according to a predetermined function, said transmittance control signals in response to data input signals being applied to the circuit, so that the transmittance signals causes the state of transmittance of the front end unit to be such as to produce images with gray tones.

9. A display method employing a device comprising:

a front end unit including an array of row electrodes and an array of column electrodes transverse to the array of row electrodes, said row electrodes

overlapping column electrodes over a layer of light modulating material when viewed in a viewing direction to define consecutive rows of pixels at the layer, so that light transmittance through the pixels is controlled by transmittance control signals applied to the row and column electrodes;

a back end unit having two or more subsections generating light of a plurality of colors, each subsection overlapping at least one corresponding row of pixels in the front end unit when viewed in the viewing direction, so that light emitted by each subsection is directed substantially towards said at least one corresponding row of pixels; and

said method comprising:

applying two or more sequences of transmittance control signals to the row and column electrodes, each sequence causing the light transmittance through the pixels to sequentially change one row at a time, defining a scanning process sequentially scanning the rows of pixels during which one row of pixels is scanned at a time, each sequence corresponding to one of said plurality of colors, wherein each sequence of transmittance control signals controls the light transmittance of the rows of pixels for passage of light of the corresponding color;

causing each subsection to emit light of one of said plurality of colors at a predetermined time delay after the application of transmittance control signals in the sequence corresponding to such color to change the light transmittance of the at least one row of pixels corresponding to such subsection for passage of light of such color, and so that said predetermined time delays for light emission of all the subsections are substantially the same.

10. The method of claim 9, said front end unit displaying color images in response to a time sequence of input signals each containing information relating to the desired state of transmittance of pixels at a particular time, said method further comprising the step of modulating said input data to generate transmittance control signals for controlling transmittance states of pixels at at least one particular time as a function of at least two input signals in the time sequence, said at least two input signals containing information relating to the desired states of transmittance of pixels at at least two different times.

11. The method of claim 10, at least one pixel exhibiting a time sequence of corresponding states of transmittance in response to a time sequence of input signals, wherein said applying step includes generating a transmittance control signal in response to a corresponding input signal in said time sequence of input signals for controlling the state of transmittance at said at least one pixel, said modulating step including storing information related to at least one state of said time sequence of transmittance states for said at least one pixel, so that when an input signal subsequent to the one corresponding to the stored state is applied to the circuit, said generating step provides a transmittance control signal that is a function of the stored transmittance state and of such input signal, thereby reducing transient errors in the gray tones of images displayed.

12. The method of claim 10, said modulating step including:

determining for at least one pixel whether a first target transmittance state for a first color corresponding to said input data signals to be displayed

at such at least one pixel is achievable within a predetermined cycle time from a previous state; and

altering said target transmittance state as well as at least one additional target transmittance state for at least an additional color when said determining step determines that said first target transmittance state is unachievable within said predetermined cycle time;

wherein said transmittance control signals are generated in accordance with the altered target transmittance states.

13. A display apparatus for displaying images in response to input signals, said apparatus comprising:

a front end unit, said unit defining therein a plurality of pixels, each pixel including at least one light shutter;

a back end unit for providing light toward the pixels in the front end unit;

a device including a lookup table, said device generating transmittance control signals in response to the input signals according to the lookup table, said device providing said transmittance control signals to the front end unit to address each pixel in the front end unit and to control the light transmittance therethrough, said light transmittance defining a state of transmittance of such pixel; and

means for causing the back end unit to produce light directed towards the front end unit to produce images according to the input signals.

14. The apparatus of claim 13, wherein for at least one pixel, said apparatus displays a sequence of images at different times at such pixel in response to a time sequence of input signals, said lookup table generating a transmittance control signal in response to

a corresponding input signal in said time sequence of input signals for controlling the state of transmittance at said at least one pixel in the front end unit, said at least one pixel exhibiting a time sequence of corresponding states of transmittance in response to said time sequence of input signals, said lookup table generating a sequence of transmittance control signals each corresponding to one of the input signals in said time sequence of input signals, said device further including:

a storage unit for storing information related to at least one state of said time sequence of transmittance states for said at least one pixel, so that when an input signal subsequent to the one corresponding to the stored state is applied to the lookup table, said lookup table provides a transmittance control signal that is a function of the stored transmittance state and of such input signal, thereby reducing transient errors in the gray tones of images displayed.

15. The apparatus of claim 14, wherein said device is a state machine that responds to an input signal and at least a present state of transmittance to produce a transmittance control signal corresponding to such input signal and information related to the next state of transmittance.

16. A method for displaying images in response to input signals employing an apparatus comprising (a) a front end unit, said unit defining therein a plurality of pixels, each pixel including at least one light shutter; (b) a back end unit generating light toward the pixels in the front end unit; said method comprising:

generating transmittance control signals in response to the input signals and according to a lookup table;

applying said transmittance control signals to the front end unit to address each pixel in the front end unit and to control the light transmittance therethrough, said light transmittance defining a state of transmittance of such pixel; and

causing the back end unit to produce light directed towards the front end unit to produce images according to the input signals.

17. The method of claim 16, wherein, in response to a time sequence of input signals, said generating step generates and said applying step applies sequentially a plurality of transmittance control signals to a pixel for sequentially addressing such pixel of the front end unit at different times and to control sequentially the light transmittance of such pixel, said sequentially applied signals forming a time sequence of transmittance control signals, said sequential light transmittances forming a time sequence of transmittance states of the pixel, each of said states corresponding to a transmittance control signal, said method further comprising:

storing information related to at least one of said transmittance states, wherein said generating step generates a transmittance control signal and information related to the next transmittance state in the sequence of transmittance states for storage, and wherein said generating step generates the next transmittance control signal in the sequence of transmittance control signals in response to the input signal and the stored information.

18. The method of claim 17, further comprising feeding back the information related to the next transmittance state in the sequence of transmittance states to a storage unit for storage.

19. The method of claim 17, wherein said generating step generates said information related to the next transmittance state in the sequence of transmittance states from the input signal.

20. The method of claim 16, said generating step including:

determining for at least one pixel whether a first target transmittance state for a first color corresponding to said input signals to be displayed at such at least one pixel is achievable within a predetermined cycle time from a previous state; and

altering said target transmittance state as well as at least one additional target transmittance state for at least an additional color when said determining step determines that said first target transmittance state is unachievable within said predetermined cycle time;

wherein said transmittance control signals are generated in accordance with the altered target transmittance states.

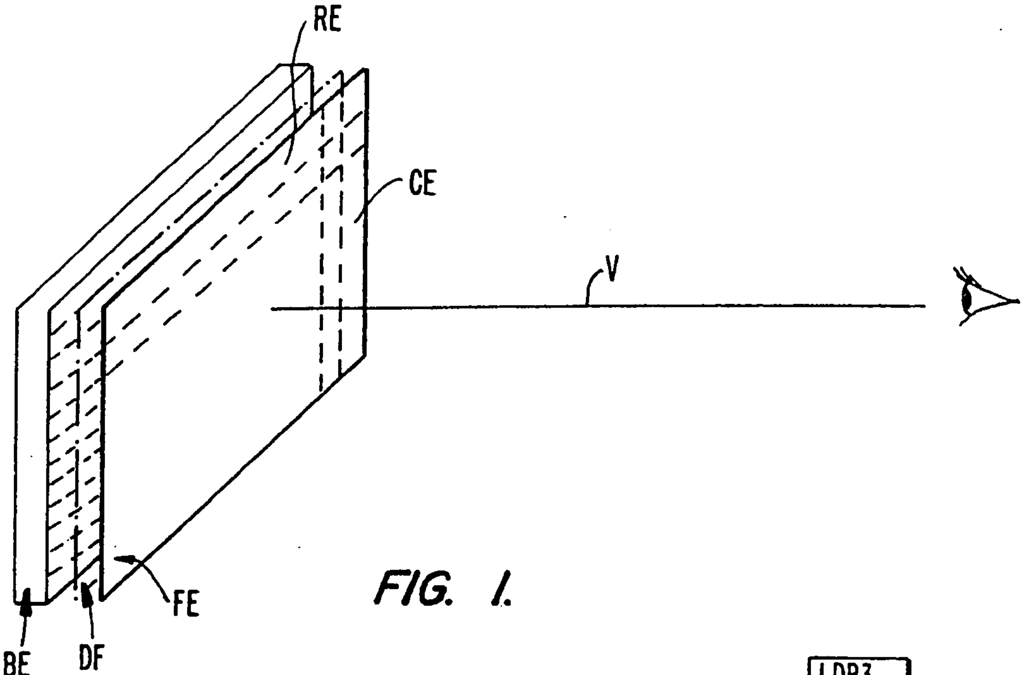
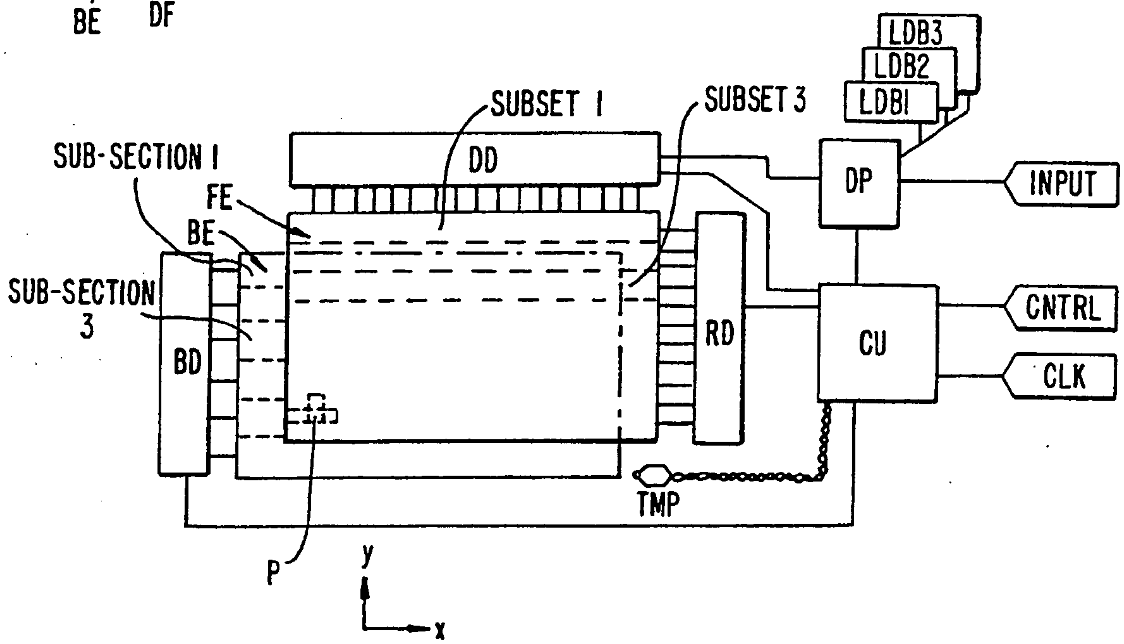

RE
CE
V
BE
DF
FE

FIG. 1.


LDB3
LDB2
LDBI
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SUBSET 3
SUB-SECTION I
DD
DP
INPUT
FE
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3
BD
RD
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CNTRL
CLK
TMP
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y
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FIG. 2.

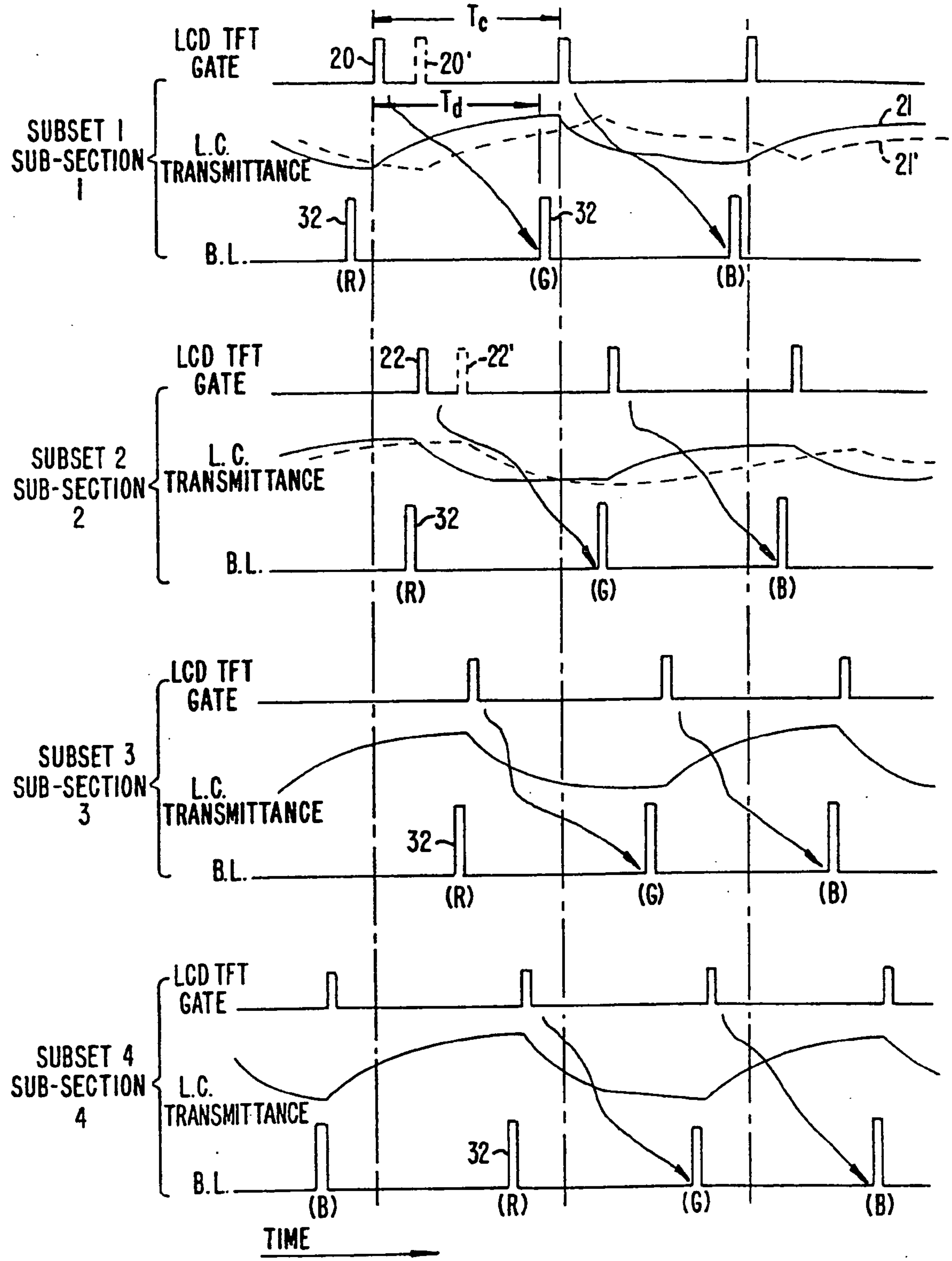

FIG. 3.

SUBSTITUTE SHEET

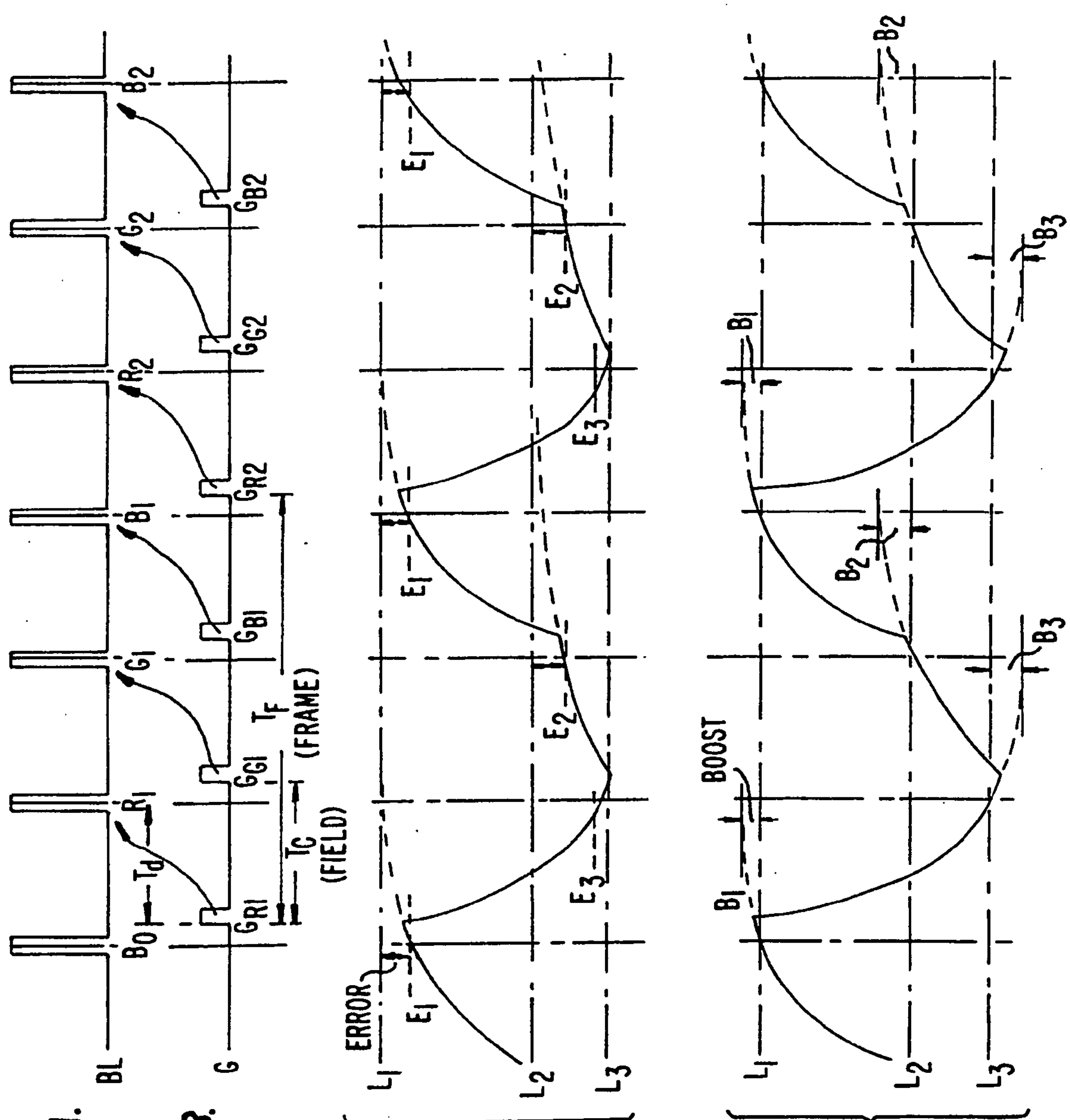

FIG. 4A.

FIG. 4B.

FIG. 4C.

FIG. 4D.

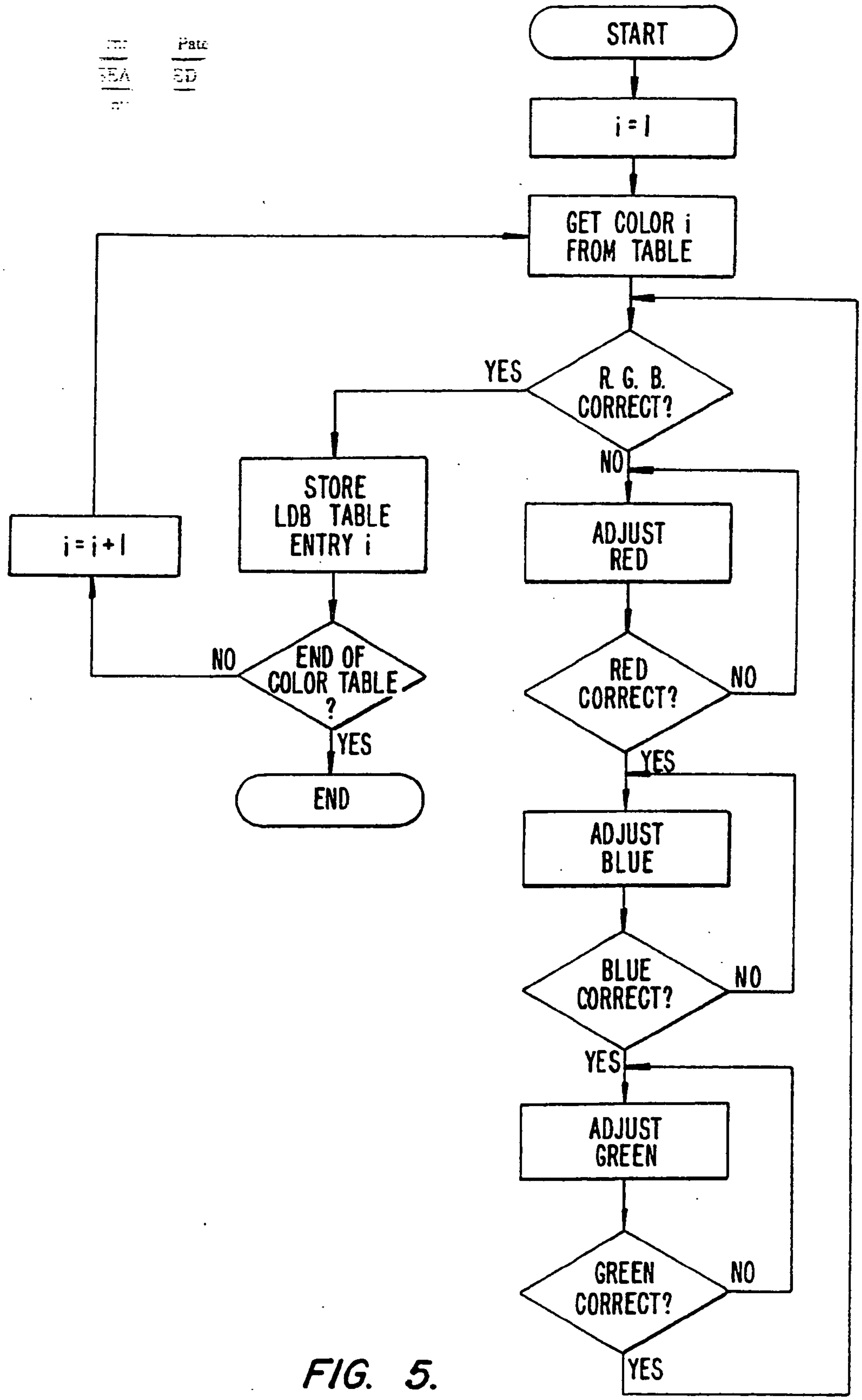
START
i = 1
GET COLOR i FROM TABLE
R. G. B. CORRECT?
YES
NO
STORE LDB TABLE ENTRY i
i = i + 1
END OF COLOR TABLE ?
NO
YES
END
ADJUST RED
RED CORRECT?
NO
YES
ADJUST BLUE
BLUE CORRECT?
NO
YES
ADJUST GREEN
GREEN CORRECT?
NO
YES

FIG. 5.

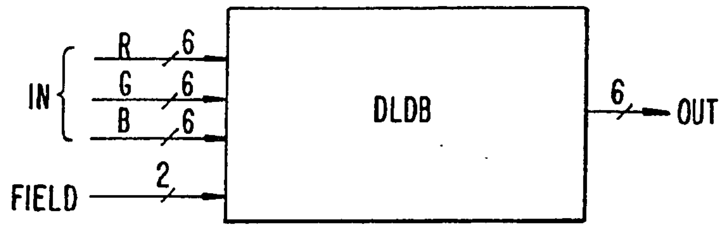

FIG. 6A.

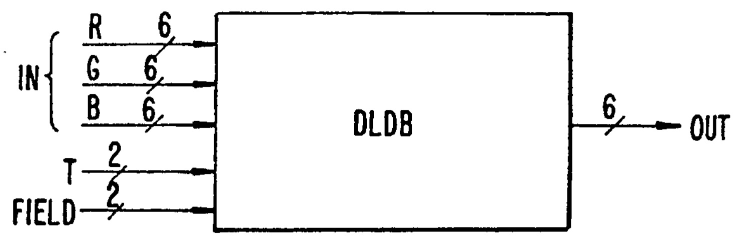

FIG. 6B.

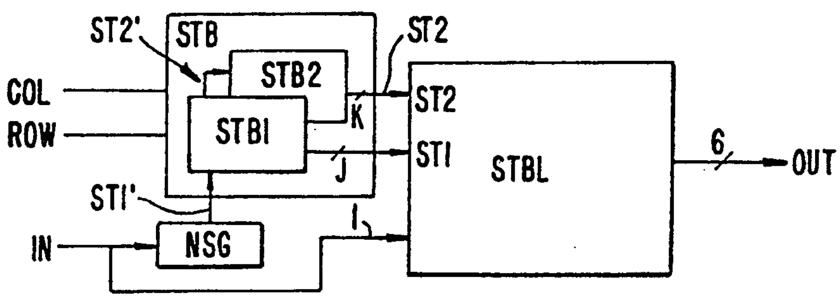

FIG. 6C.

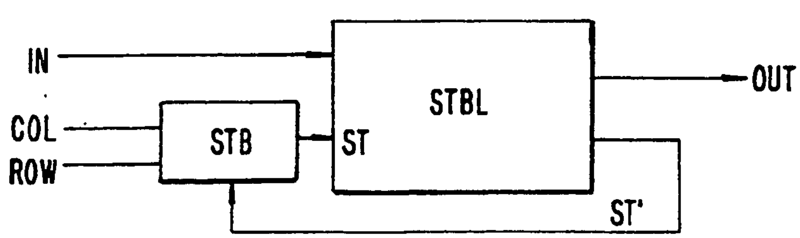

FIG. 6D.

SUBSTITUTE SHEET

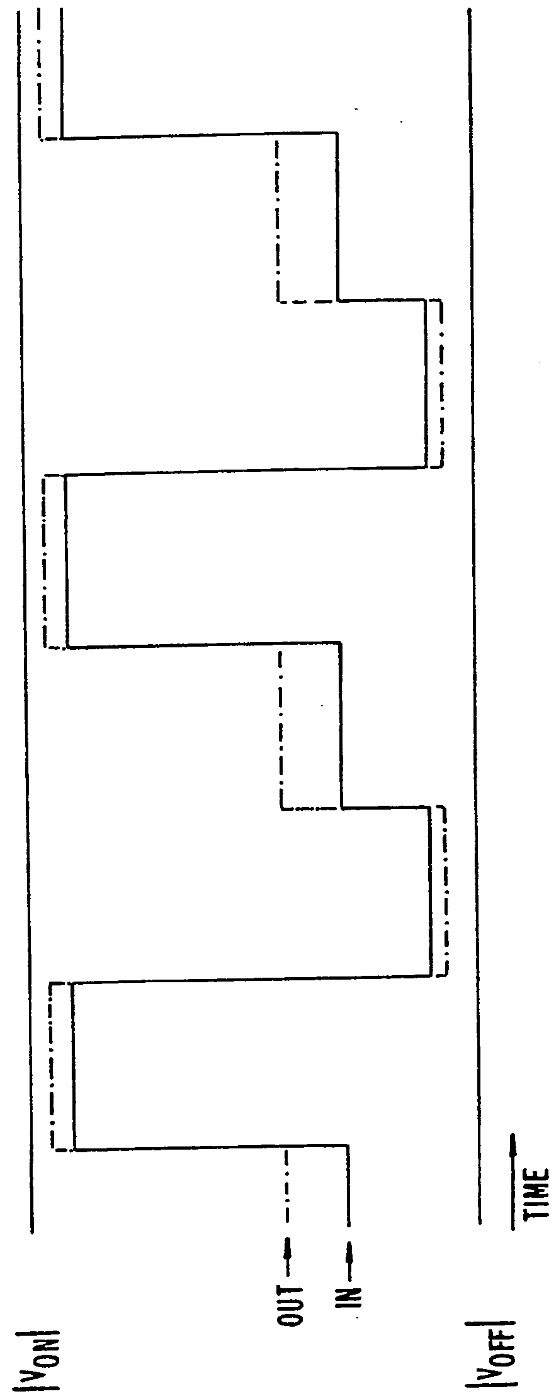

FIG. 6E.

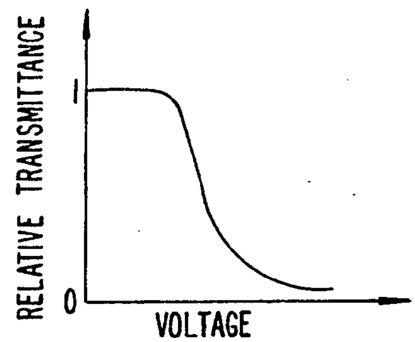

FIG. 7A.

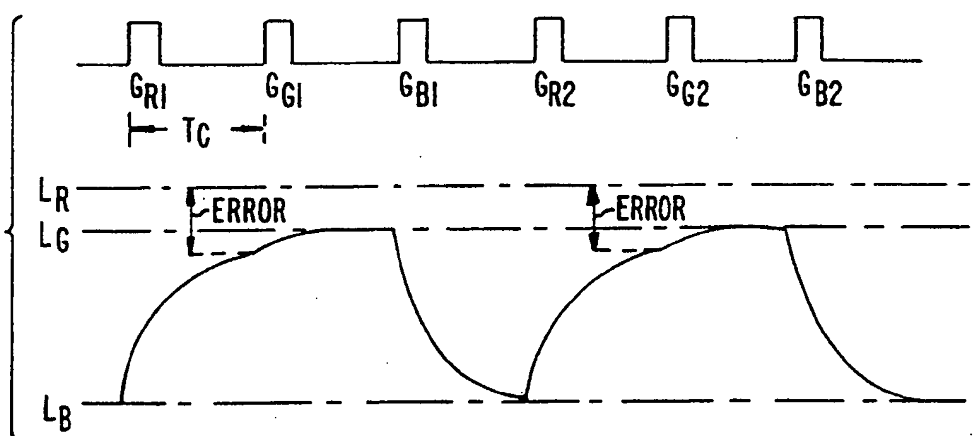

FIG. 7B.

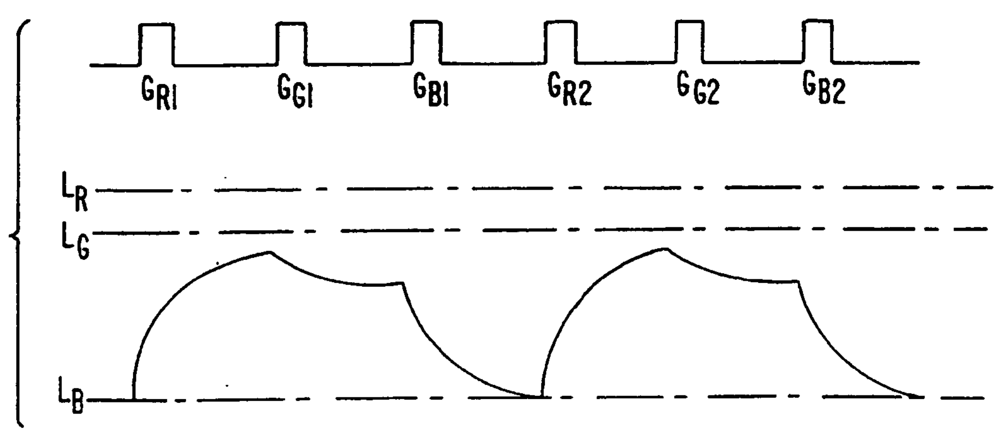

FIG. 7C.

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US93/10062

A. CLASSIFICATION OF SUBJECT MATTER

IPC(5) :G09G 3/36
US CL : 345/102, 88
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 345/4, 5, 88, 94, 101, and 102; 359/48, 86

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US, A, 5,128,782 (WOOD) 07 JULY 1992, note the abstract and the summary of the invention.	1-20

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be part of particular relevance
"E" earlier document published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search: 28 December 1993

Date of mailing of the international search report: FEB 18 1994

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